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FLAMMABILITY CHARACTERISTICS OF GLASS REINFORCED EPOXY COMPOSITE MATERIALS

February 1992

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FINAL REPORT

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Watertown, Massachusetts 02172-0001

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FLAMMABILITY CHARACTERISTICS OF GLASS REINFORCED EPOXY COMPOSITE MATERIAL

by

Archibald Tewarson

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ABSTRACT

Fiber reinforced composite (FRC) materials are used extensively because of their favorable physico-chemical properties and high strength-to-weight ratio. The use of composites in Army vehicles as a means of decreasing weight and enhancing survivability, without reducing personnel safety, has been under study for some time. Although FRC materials are very attractive in terms of their physico-chemical properties, concern for possible fire hazards is understandable, as organic polymers are a major constituent of the materials.

This report presents flammability evaluation results for three FRC materials (MTL #6 to #7). In this evaluation, the latest technology developed at Factory Mutual Research Corporation (FMRC) was used.

In comparison to ordinary combustibles, such as cellulosics and most non-fire retarded plastics, the three FRC materials have higher resistance to ignition and flame propagation. In comparison to the FRC materials (MTL #1 to #5) investigated in the previous study for the Army Materials Technology Lab, the three FRC materials were found to ignite more easily, and flame propagated beyond the ignition zone. Also, these three materials generated significantly higher amounts of material vapors, CO, smoke and heat than the materials examined earlier (MTL #1 to #5). Thus passive fire protection is required for these materials. This protection can be provided by surface coatings or by surface lamination using highly fire resistant FRC materials such as the fiberglass phenolic examined in the previous study.

The Halon 1301 flame extinction data for the samples were found to be consistent with the design of the current suppression system for the crew compartment of Army combat vehicles.

It is strongly recommended that the scientifically based FIRE PROPAGATION INDEX (FPI) concept, developed at Factory Mutual Research Corporation, be adopted for the realistic flammability evaluation and screening of FRC materials for Army applications.

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I

INTRODUCTION

Fiber reinforced composite (FRC) materials are used extensively because of their favorable physico-chemical properties, including high strength-to-weight ratio and excellent resistance to ballistic penetration. The use of composites in Army vehicles as a means of decreasing weight and enhancing survivability, without reducing personnel safety, has been under study for some time. The U.S. Army Materials Technology Laboratory (AMTL) has successfully demonstrated that a ground vehicle turret could be fabricated from FRC materials; since then, the technology has been applied to the fabrication of a composite vehicle hull[1], as well as more complex vehicle components.

Although FRC materials are very attractive in terms of their physico-chemical properties, concern for possible fire hazards is understandable, as organic polymers are one of the major constituents of the materials (approximately 30% by weight or 50% by volume). It is, therefore, necessary that the flammability of FRC materials be determined and compared with that of other materials. Several FRC materials (MTL # 1 to 5) have already been investigated[2,3]. This report describes results for the flammability evaluation of three additional glass fiber reinforced epoxy composite materials listed in Table 1.

TABLE 1

GLASS FIBER REINFORCED EPOXY COMPOSITE MATERIALS TESTED IN THIS STUDY*

Sample Number	Designation	Manufacturer
MTL #6	CE-321R Epoxy/Glass	Ferro Corporation
MTL #7	MXB7701/24 oz. WR, Epoxy/Glass	ICI Fiberite
MTL #8	CYCOM 5920 (also CYCOM X920)	Cyanamid Company

* Nominal compositions, 70% glass-30% resin. Information supplied by William Haskell III, Materials Engineer/Plastics, Army Materials Technology Laboratory, Watertown, MA.

In this study, flammability evaluations were performed using the latest technology developed at the Factory Mutual Research Corporation (FMRC)[4-8]. The underlying principles of this evaluation are briefly reviewed in the Appendix. All the experiments were performed in FMRC's 50 kW-Scale Flammability Apparatus, shown in Figure 1. In this report, data for FRC materials MTL #1 to 5, examined in the previous study for the Army Materials Technology Laboratory[2,3], have been included for comparison.

II
RESULTS

2.1 IGNITION

Times to piloted ignition at various external heat flux values were measured for horizontal, 0.009 m^2 samples. From the square root of the inverse of time to ignition versus external heat flux, Critical Heat Flux (CHF) and Thermal Response Parameter (TRP) values were derived[2,3,7]. For materials with higher CHF and TRP values, resistance to ignition and flame propagation is higner; therefore, larger ignition and external heat sources are required to assist flame propagation.

CHF and TRP values for MTL Samples #6, 7, and 8 and MTL Samples #1 to 5, examined previously[2,3], are shown in Figures 2 and 3, respectively. CHF values for MTL Samples #6, 7 and 8 are lowest and comparable to those for MTL Samples #1 and 3. The TRP values for the three new samples are comparable to those for MTL Samples #1, 2 and 4.

Thus FRC MTL Samples #6, 7 and 8 exhibit a low ignition resistance and should be provided with additional protection.

2.2 GENERATION RATE OF MATERIAL VAPOR PER UNIT EXTERNAL HEAT FLUX

This parameter is used to assess the amount of combustible vapor generation expected when material burns. The generation rate of material vapor is also described in terms of heat of gasification (see Appendix). The higher the value of this parameter, the greater the amount of combustible vapor generated.

The generation rate of material vapor was determined by exposing 0.009 m^2 horizontal samples to various external heat flux values and by measuring the mass loss rate by a load cell in the 50 kW-Scale Flammability Apparatus.

Results for MTL Samples #6, 7 and 8 are shown in Fig. 4. In the figure, data for the peak values of the generation rate of material vapors are divided by the external heat flux. Data for MTL Samples #1 to 5, examined in the previous study[2,3], are also included in the figure.

The value of the generation rate parameter is highest for MTL Samples #6, 7 and 8, comparable to MTL #3. These materials are expected to generate larger amounts of combustible vapors than highly fire resistant FRC materials. Therefore, these materials, #6, #7 and #8, need a high level of protection.

2.3 GENERATION RATE OF CARBON MONOXIDE PER UNIT OF EXTERNAL HEAT FLUX

This parameter is used to assess the amount of carbon monoxide (CO) generation expected when a material burns. The higher the value of this parameter, the greater the amount of CO generated.

The generation rate of CO was measured for 0.009 m^2 horizontal samples exposed to various external heat flux values, in the 50 kW-Scale Flammability Apparatus. The results are shown in Fig. 5, where the generation rate of CO is divided by the external heat flux. Data for MTL Samples #1 to 5, examined in the previous study[2,3], have also been included in the figure.

The value of the parameter is highest for the MTL Samples #6, 7 and 8. These materials are expected to generate larger amounts of CO than highly fire resistant FRC materials and thus need additional protection.

2.4 MASS OPTICAL DENSITY OF SMOKE

Mass optical density (MOD) is used to assess the amount of smoke generation and visibility reduction during fires. The higher the value of MOD, the greater the amount of smoke generated and the greater the reduction in visibility.

MOD (m^2/g) is calculated by multiplying the optical density (m^{-1}) by the total volumetric flow rate (m^3/s) and dividing by the generation rate of material vapors (g/s).

In this study, 0.009 m^2 samples of MTL #6, 7 and 8 were mounted horizontally and exposed to various external heat flux values. Measurements were made for the optical density and total volumetric flow rate of the product-air mixture. Large amounts of thick black smoke were generated from these samples. The MOD values are shown in Fig. 6. MOD values for MTL Samples #1 to 5, determined in the previous study[2,3], have also been included in the figure.

In Fig. 5, MOD values for MTL Samples #6, 7 and 8 are high compared to highly fire resistant FRC materials; thus, fire protection is needed.

2.5 CHEMICAL HEAT RELEASE RATE PER UNIT OF EXTERNAL HEAT FLUX

This parameter is used to predict the amount of heat generated in a fire. The higher the value of the parameter, the greater the amount of heat generated. Heat generated in the reactions leading to the formation of CO and CO_2 and depletion of oxygen is defined as the chemical heat release rate. The chemical heat release rate for horizontal 0.009 m^2 samples exposed to various external heat flux values was measured.

Peak values of chemical heat release rate divided by the external heat flux are shown in Fig. 7 for MTL Samples #6, 7 and 8 and MTL Samples #1 to 5. The values of the parameter for MTL Samples #6, 7 and 8 samples are again higher than the values for highly fire resistant FRC materials and thus fire protection is needed.

2.6 FIRE PROPAGATION

Fire propagation behavior is characterized in terms of Fire Propagation Index (FPI), expressed as the ratio of the radiative heat release rate (per unit width to the one-third power) to the TRP. The higher the FPI value, the higher the fire propagation rate. For materials with FPI values less than 8, fire propagation beyond the ignition zone is unlikely; for materials with FPI values equal to or greater than 8, fire is expected to propagate beyond the ignition zone and fire protection is needed.

FPI values for MTL samples #6, 7 and 8 were determined for 0.61 m long and 0.10 m wide vertical sheets in a 40% oxygen environment with the bottom 0.15 m in the ignition zone (50 kW/m^2 of external heat flux with a pilot flame). FPI values were calculated as follows: 1) chemical heat release rate (in kW), measured during fire propagation, was multiplied by 0.40 to convert it to radiative heat release rate; 2) radiative heat release rate was divided by the width of the sheet (in meters); 3) the radiative heat release rate per unit width was raised to the one-third power, and then divided by the TRP value in ($kW\text{-}s^{1/2}/m^2$); the result was multiplied by 1000. Visual observations of flame propagation were difficult for these samples, as large amounts of smoke were generated.

Table 2 and Figure 8 show FPI values for MTL Samples #6, 7 and 8. FPI values for MTL Samples #1 to 5 have also been included in the figure for comparison. FPI values for MTL Samples #6, 7 and 8, as well as for MTL Samples #1 and 3, are greater than or equal to 8. Thus, flame propagation beyond the ignition zone is expected, and passive or active fire protection is needed. Active fire protection can be provided by Halon for the crew compartment. Passive fire protection can be provided by surface coating or lamination with highly fire resistant FRC material such as the fiberglass phenolic examined in the previous study.

TABLE 2

FIRE PROPAGATION INDEX VALUES FOR FIBER REINFORCED COMPOSITE MATERIALS*

MTL # Sample	Thickness (mm)	Peak FPI Value
1	4.8	13.3
3	4.8	9.7
4	4.8	7.8
5	3.2	3.2
6	4.4	8.8
7	4.8	11.3
8	4.4	9.8

* For 0.61 m long 0.10 m wide vertical sheets in a 40% oxygen environment. Bottom 0.15 m exposed to 50 kW/m^2 of external heat flux in the presence of a pilot flame.

2.7 FLAME EXTINCTION BY HALON 1301

Flame extinction by Halon 1301 was determined for 0.009 m^2 horizontal samples of MTL Samples #6, 7 and 8 exposed to an external heat flux value of 60 kW/m^2, under coflow conditions. Halon 1301 was added to the air flow.

Figure 9 shows the volume percent of Halon 1301 required for flame extinction for MTL samples #6, 7 and 8 along with values for MTL samples #1 to 5. The data show that flame extinction occurs well within 4% by volume of Halon 1301. This range is consistent with the design of the current suppression system for the crew compartments of Army combat vehicles.

III
CONCLUSION

The following can be concluded for MTL Samples #6, 7 and 8:

1) The samples have low ignition resistance in comparison to highly fire resistant FRC materials; thus, fire protection is needed;
2) The samples generate large amounts of combustible vapors, carbon monoxide, smoke and heat compared to highly fire resistant FRC materials; thus, fire protection is needed;
3) Flame is expected to propagate beyond the ignition zone; thus, fire protection is needed;
4) Flame extinction by Halon 1301 occurs within 4% by volume. This range is consistent with the design of the current suppression systems for the crew compartment;
5) Both active and passive fire protection are needed. Active fire protection can be provided by Halon. Passive fire protection can be provided by surface coating or lamination with highly fire resistant FRC material such as the fiberglass phenolic examined in the previous study.

IV
RECOMMENDATION

It is strongly recommended that the Fire Propagation Index (FPI) concept be adopted for the realistic flammability evaluation of FRC materials for Army vehicles.

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APPENDIX

IGNITION

Ignition experiments are performed to measure time to ignition, t_{ig}, as a function of external heat flux, $\dot{q}''_e$. For thermally thick materials, the following linear relationship is satisfied[7]:

$$t_{ig}^{-1/2} = (4/\pi)^{1/2}\dot{q}''_e/K \qquad (1)$$

where t_{ig} is in seconds and $\dot{q}''_e$ is in kW/m^2 and $K = (\kappa\rho c_p)^{1/2}(T_{ig}-T_{sf})$, is designated as the THERMAL RESPONSE PARAMETER (TRP) for the solid (kW-s$^{1/2}$/m^2); κ is the thermal conductivity (kW/m-K); c_p is the specific heat (kJ/kg-K); ρ is the density (kg/m^3); T_f is the flame temperature (K); T_{ig} is the ignition temperature (K); T_{sf} is the initial surface temperature (K).

GENERATION RATE OF MATERIAL VAPORS PER UNIT OF EXTERNAL HEAT FLUX

The following relationship is found between the mass loss rate ($\dot{m}''$) and external heat flux ($\dot{q}''_e$)[7]:

$$\dot{m}'' = (\dot{q}''_e + \dot{q}''_f - \dot{q}''_{rr})/\Delta H_g \qquad (2)$$

where $\dot{m}''$ is in g/m^2-s, $\dot{q}''_f$ is the flame heat flux (kW/m^2), $\dot{q}''_{rr}$ is the surface reradiation loss (kW/m^2), and ΔH_g (kJ/g) is the gasification,[7]:

$$\Delta H_g = \int_0^{T_v} c_p\, dT + \Delta H_v \qquad (3)$$

where ΔH_v is the heat of vaporization (kJ/g) and T_v is the vaporization temperature (K).

For $\dot{q}''_e >> \dot{q}''_f - \dot{q}''_{rr}$,

$$\dot{m}''/\dot{q}''_e = 1/\Delta H_g \qquad (4)$$

GENERATION RATE OF CARBON MONOXIDE PER UNIT OF EXTERNAL HEAT FLUX

The generation rate of carbon monoxide (CO) per unit external heat flux (q''_e) can be expressed as:

$$\dot{G}''_{CO}/\dot{q}''_e \;=\; y_{CO}\,\dot{m}''/\dot{q}''_e \tag{5}$$

where y is the yield of CO (g/g).

For $\dot{q}''_e >> \dot{q}''_f - \dot{q}''_{rr}$,

$$y_{CO}\dot{m}''/\dot{q}''_e = y_{CO}/\Delta H_g \tag{6}$$

MASS OPTICAL DENSITY

Mass Optical Density (MOD) is expressed as:

$$MOD = \log_{10}(I_0/I)V/mL \tag{7}$$

where I/I_0 is the fraction of light transmitted through smoke, V is the total volumetric flow rate of smoke (m^3/s), m is the mass loss rate (g/s) and L is the optical path length (m).

HEAT RELEASE RATE PER UNIT OF EXTERNAL HEAT FLUX

Heat release rate in fire is defined as the chemical heat release rate ($\dot{Q}_{ch}$) and has a convective and a radiative component. It is determined from the generation rates of CO and CO_2:

$$\dot{Q}_{ch} \;=\; \Delta H^*_{CO_2}\,\dot{G}_{CO_2} + \Delta H^*_{CO}\,\dot{G}_{CO} \tag{8}$$

$$\Delta H^*_{CO_2} \;=\; \Delta H_T/\Psi_{CO_2} \tag{9}$$

$$\Delta H^*_{CO} \;=\; (\Delta H_T - \Delta H_{CO}\Psi_{CO})/\Psi_{CO} \tag{10}$$

where $\dot{Q}_{ch}$ is in kW and $\dot{G}_{CO}$ and $\dot{G}_{CO_2}$ are the generation rates of CO and CO_2 respectively (g/s), $\Delta H^*_{CO_2}$ is the heat of combustion per unit mass of CO_2 generated (kJ/g), ΔH^*_{CO} is the heat of combustion per unit mass of CO generated (kJ/g), ΔH_T is the net heat of complete combustion (kJ/g), and Ψ_{CO} and Ψ_{CO_2} are the maximum possible theoretical yields of CO and CO_2, respectively (g/g).

FIRE PROPAGATION

Fire Propagation is the movement of a flame across the surface of a material, as it is fed by the vapors of the pyrolyzing material. Flame spread governs fire hazards and protection requirements and thus is one of the most important measurements. The rate of movement of the pyrolysis front on the surface is defined by the fire propagation rate:

$$S = dX_p/dt \tag{11}$$

where S is the flame spread rate (mm/s or m/s) and X_p is the pyrolysis height (mm or m).

The flame spread process is divided into three categories: 1) accelerating, where S is a direct function of time; 2) non-accelerating, where S is independent of time; and 3) decelerating or non-propagating, where S decreases with time or the flame spread is limited to the ignition zone. For thermally thick materials with concurrent air flow, S is expressed as[5,6]:

$$S^{1/2} = (\dot{q}''_f)\Delta^{1/2}/K \tag{12}$$

where $\dot{q}''_f$ is the maximum flame heat flux at the pyrolysis front per unit surface area (kW/m^2) and $(\dot{q}''_f)\Delta^{1/2}$ is expressed as $(\chi_{rad}\dot{Q}_{ch}/d)^{1/3}$, where χ_{rad} is the radiative fraction of the combustion efficiency, Q_{ch} is the chemical heat release rate (kW), d is the width of the sheet (m) and K is defined in Eq. (1). Substitution of these quantities in Eq. (10) and multiplied by 1000, defines the FIRE PROPAGATION INDEX (FPI):

$$FPI = \left[(\chi_{rad}\dot{Q}_{chem}/d)^{1/3}/(\kappa\rho c_p)_s{}^{1/2}(T_{ig}-T_{sf})\right] \times 1000 \tag{13}$$

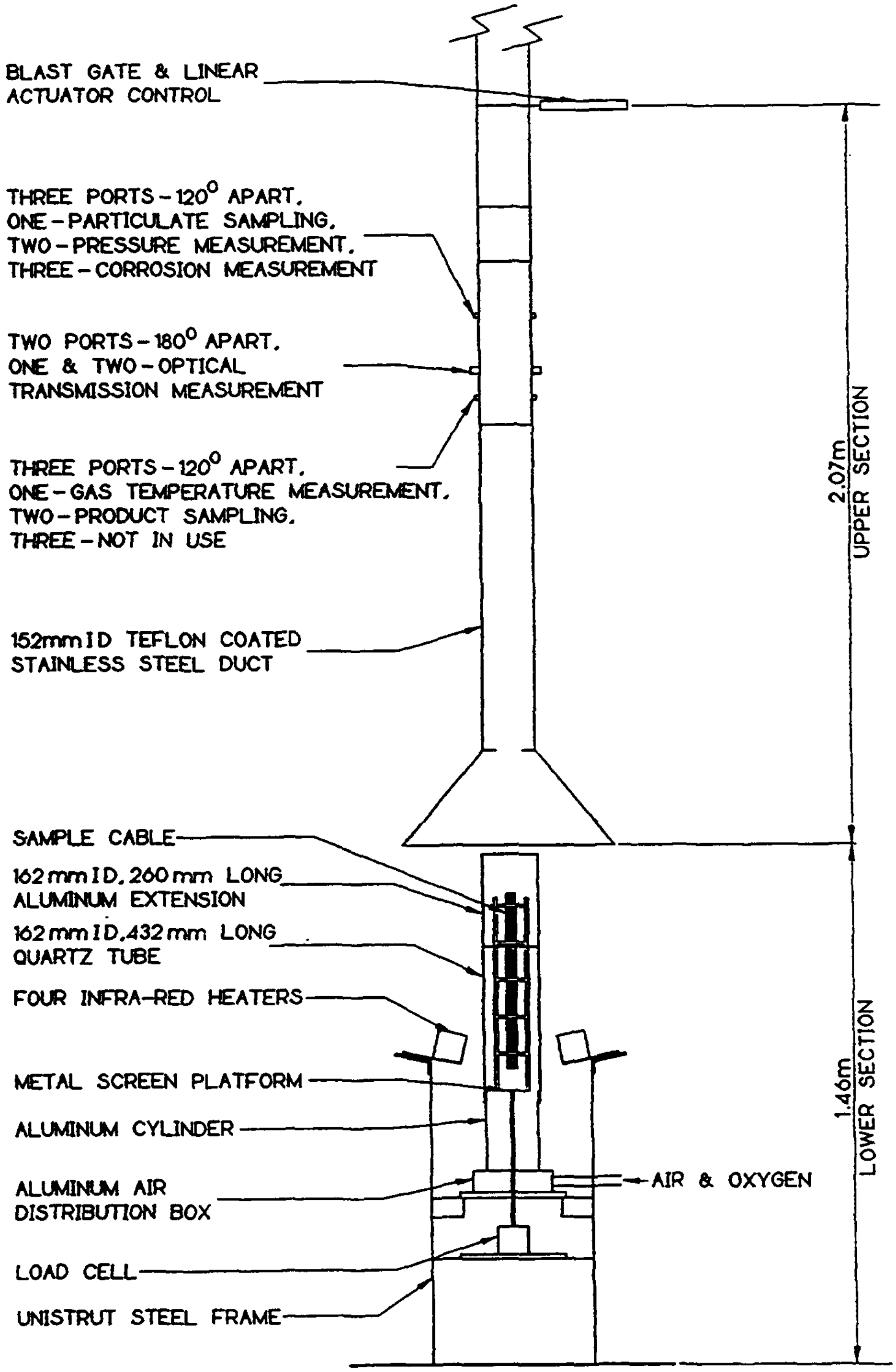

Figure 1. 50 kW-Scale Flammability Apparatus.

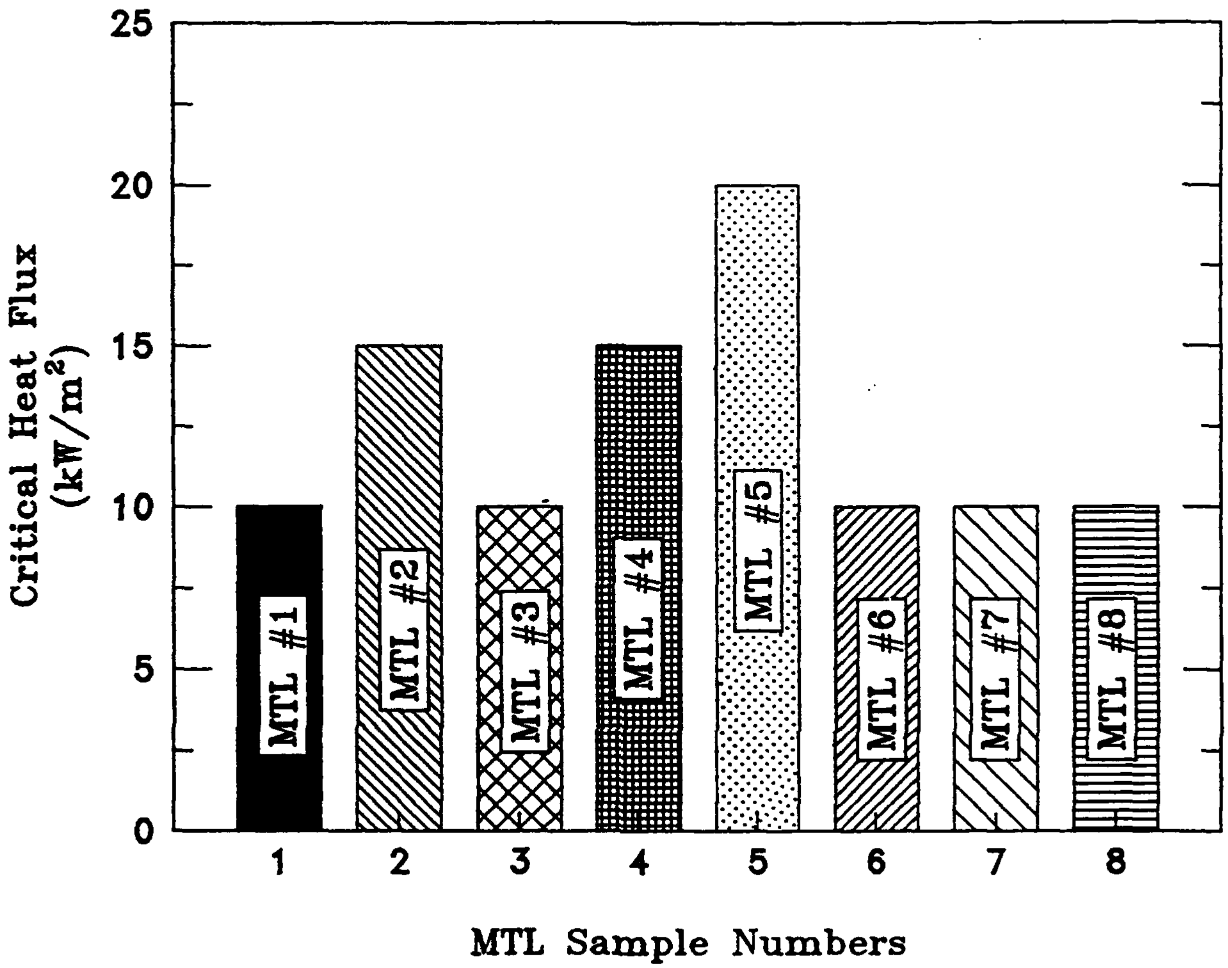

Figure 2. Critical Heat Flux for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

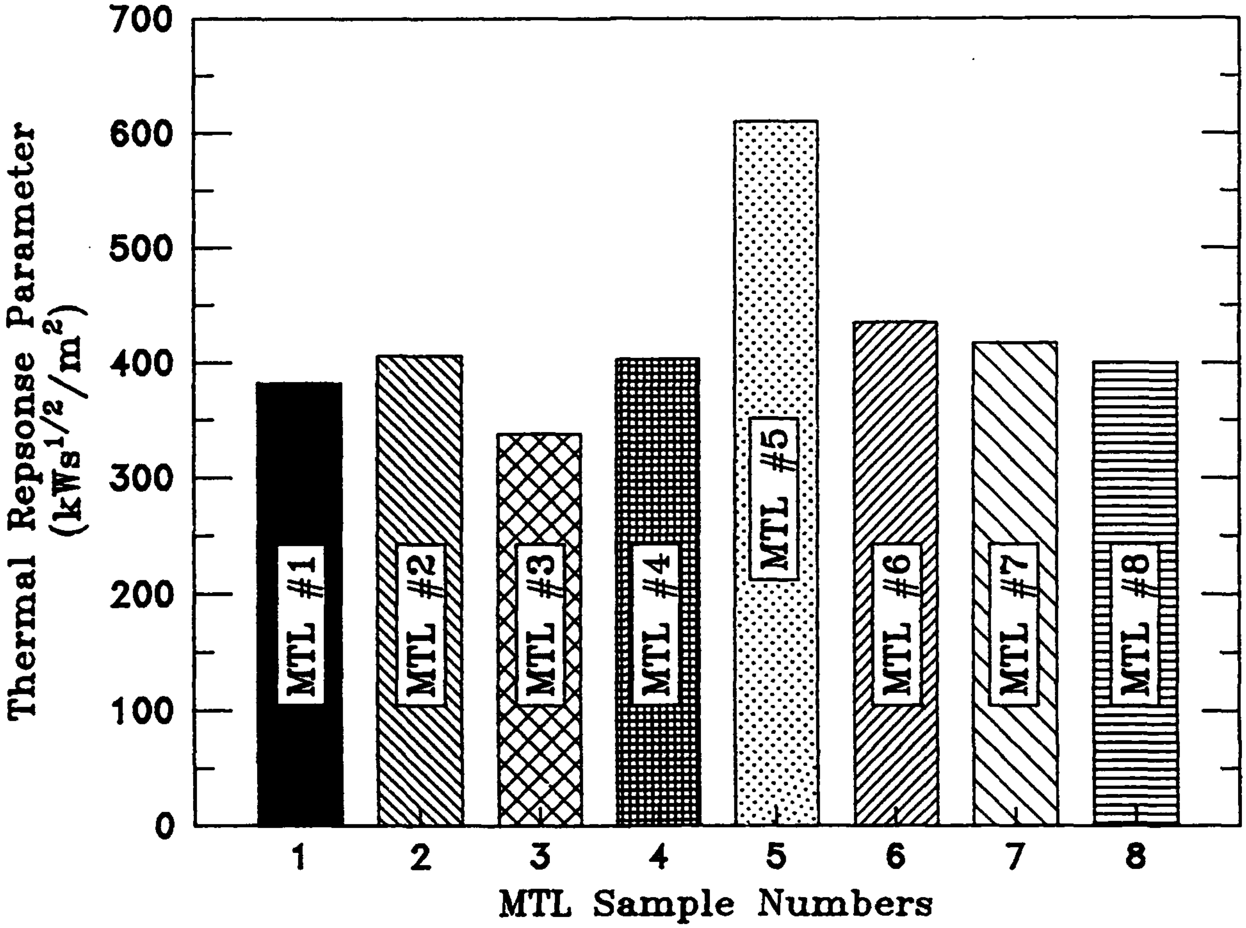

Figure 3. Thermal Response Parameter for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

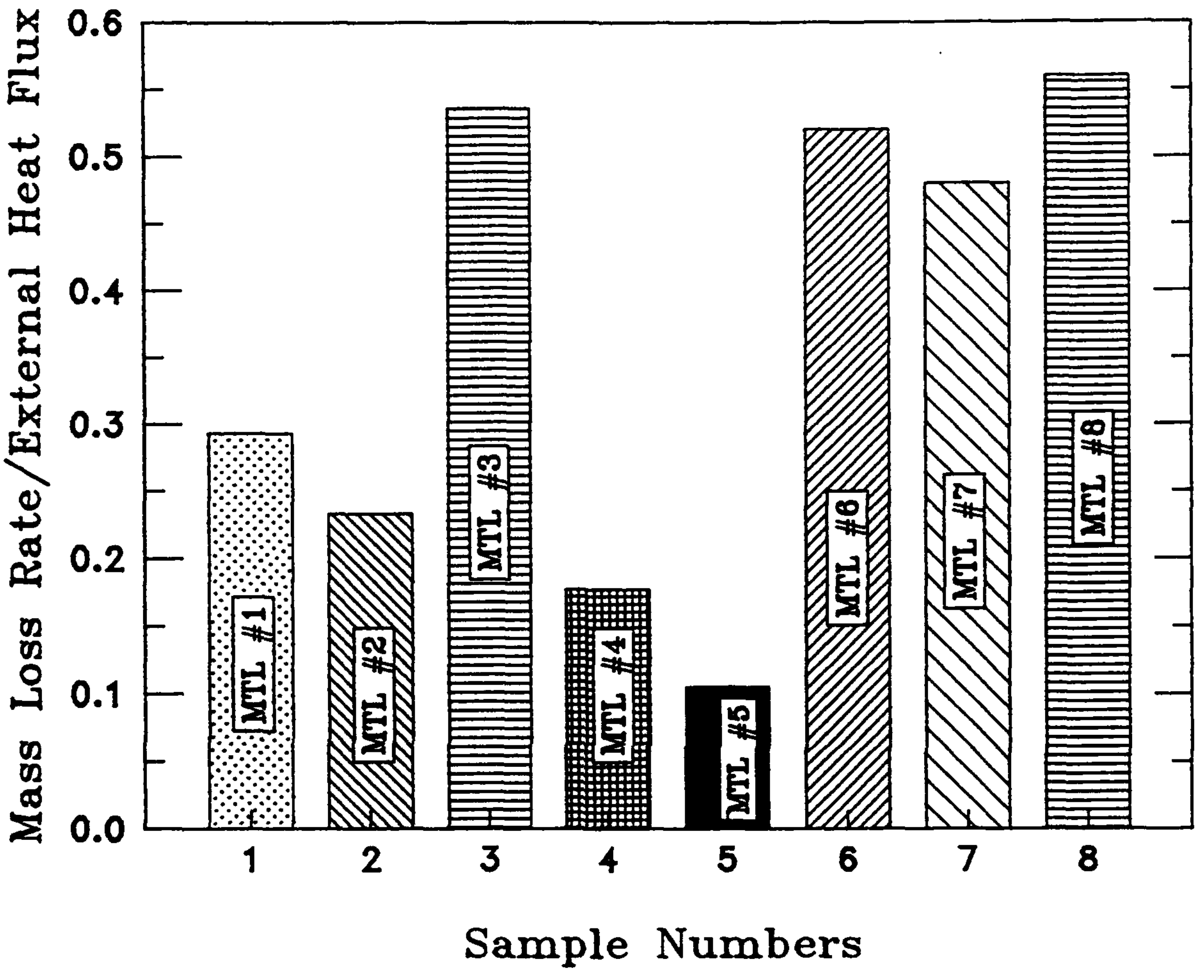

Figure 4. Peak Mass Loss Rate Per Unit External Heat for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

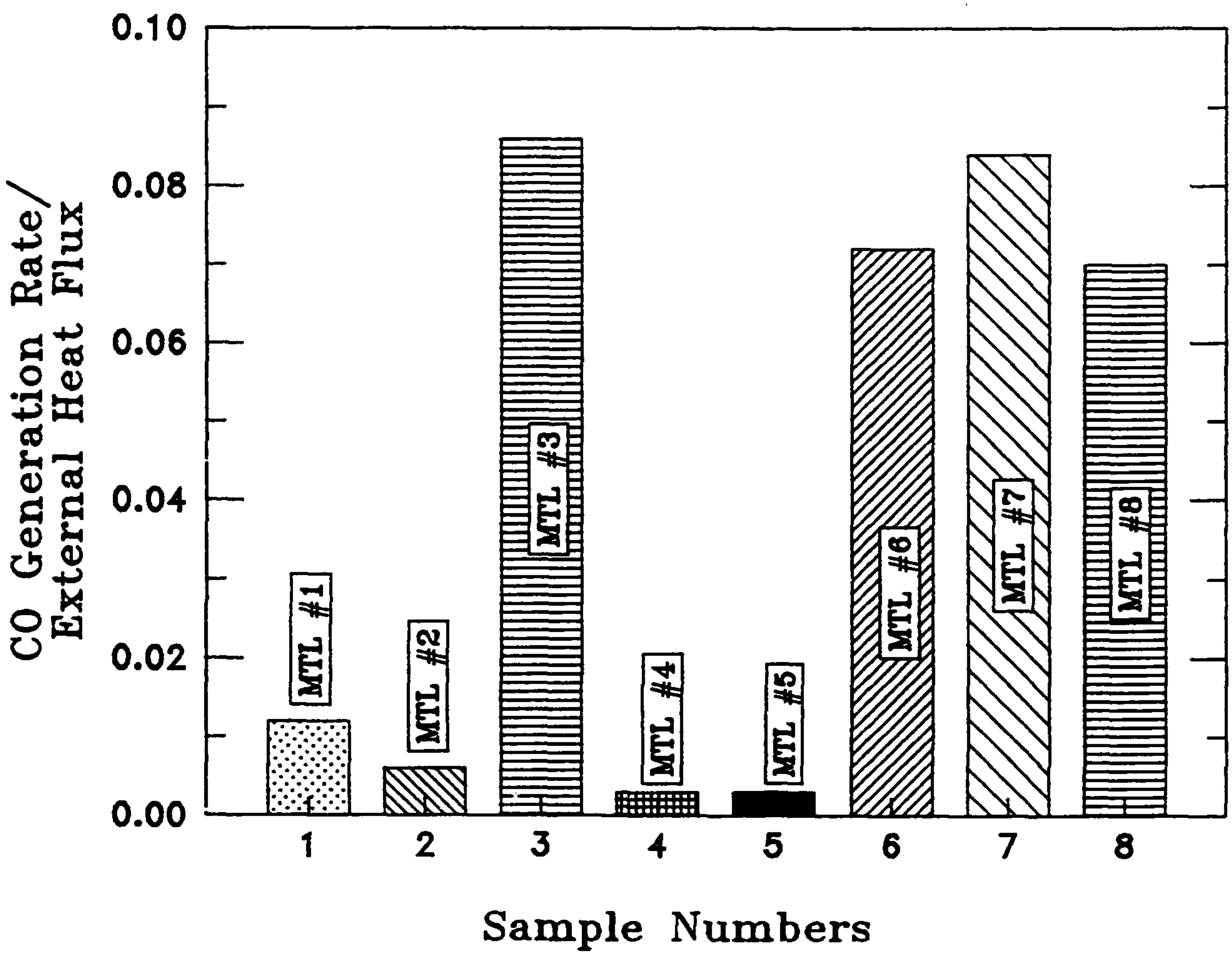

Figure 5. Peak Generation Rate of Carbon Monoxide Per Unit External Heat for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

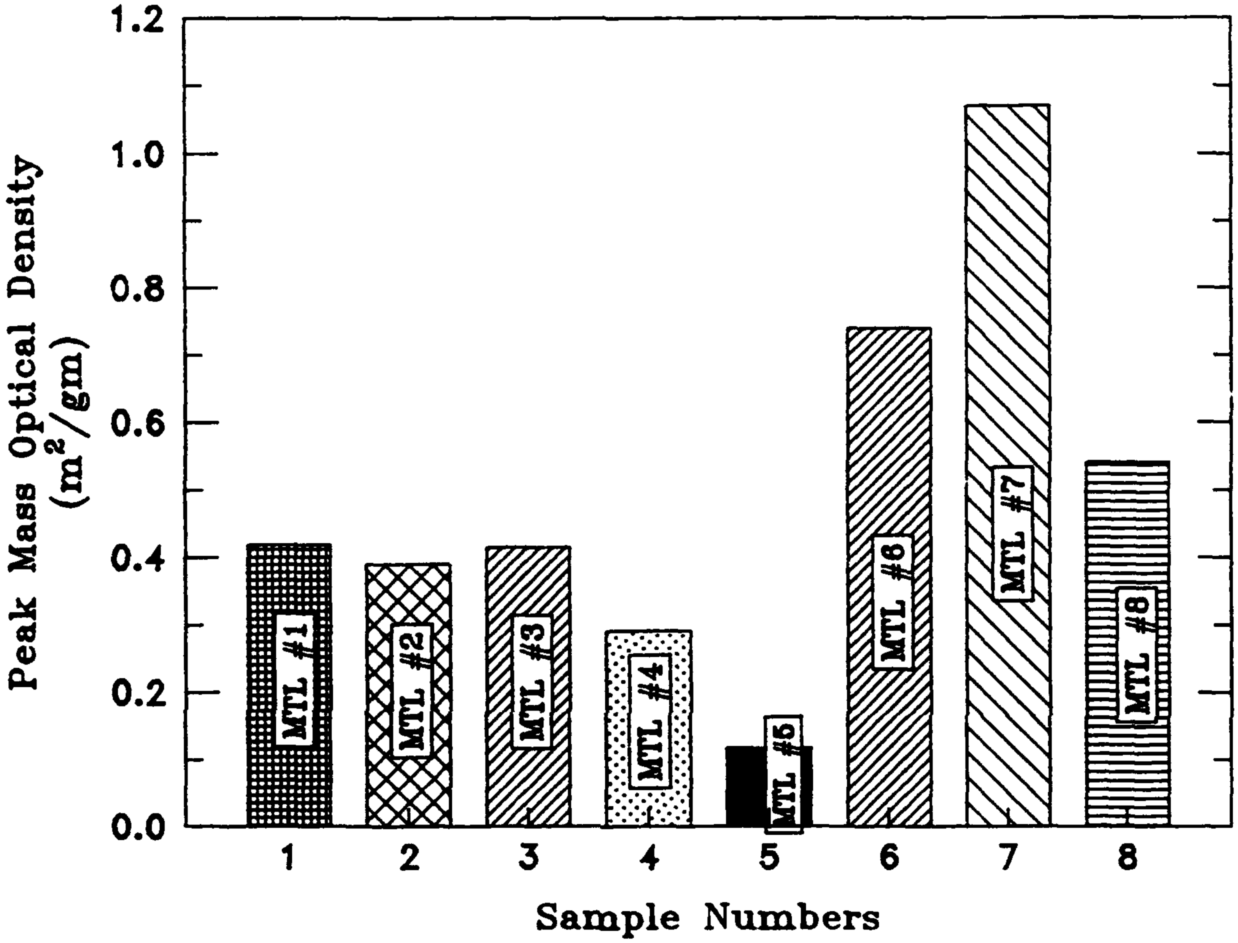

Figure 6. Peak Mass Optical Density of Smoke for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

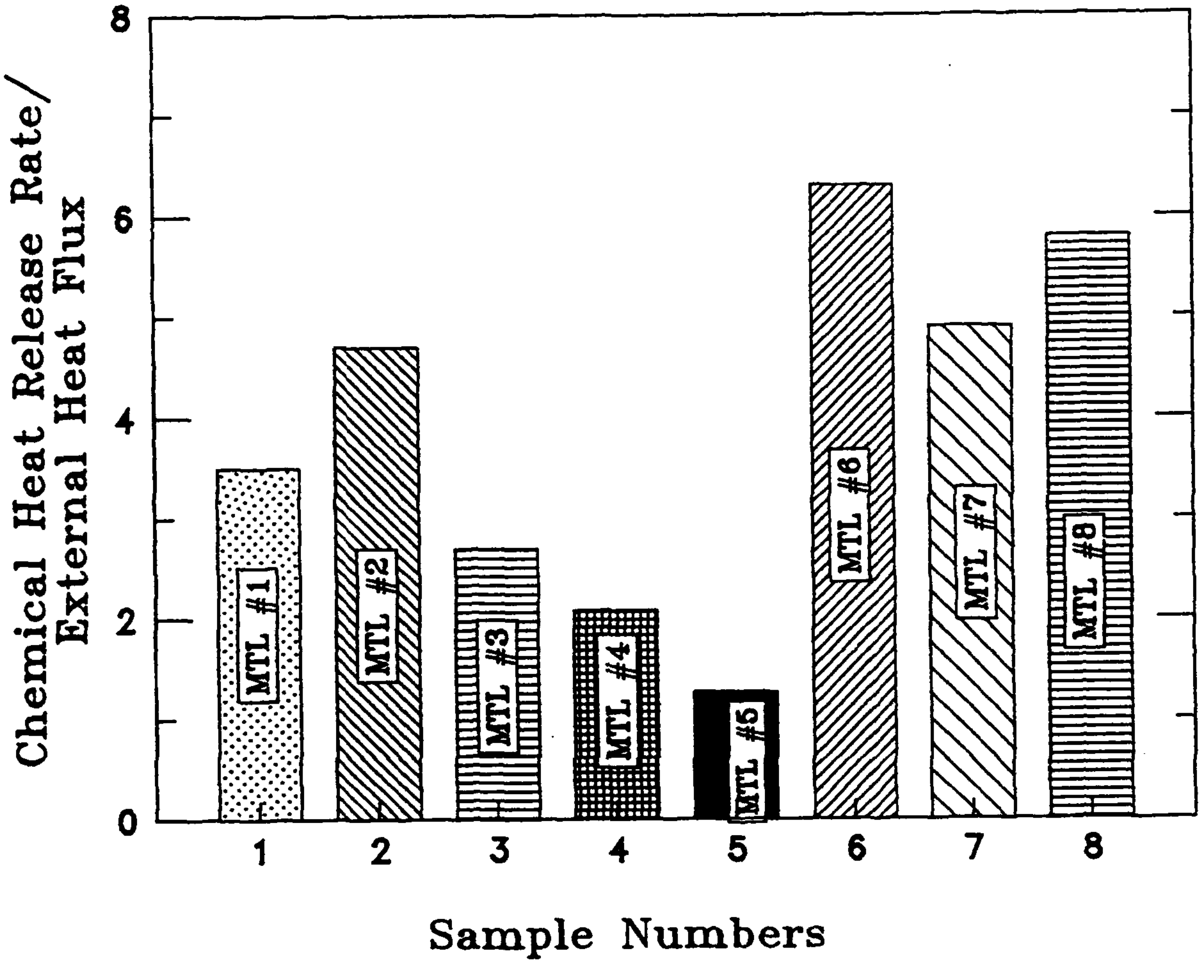

Figure 7. Peak Chemical Heat Release Rate Per Unit External Heat for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

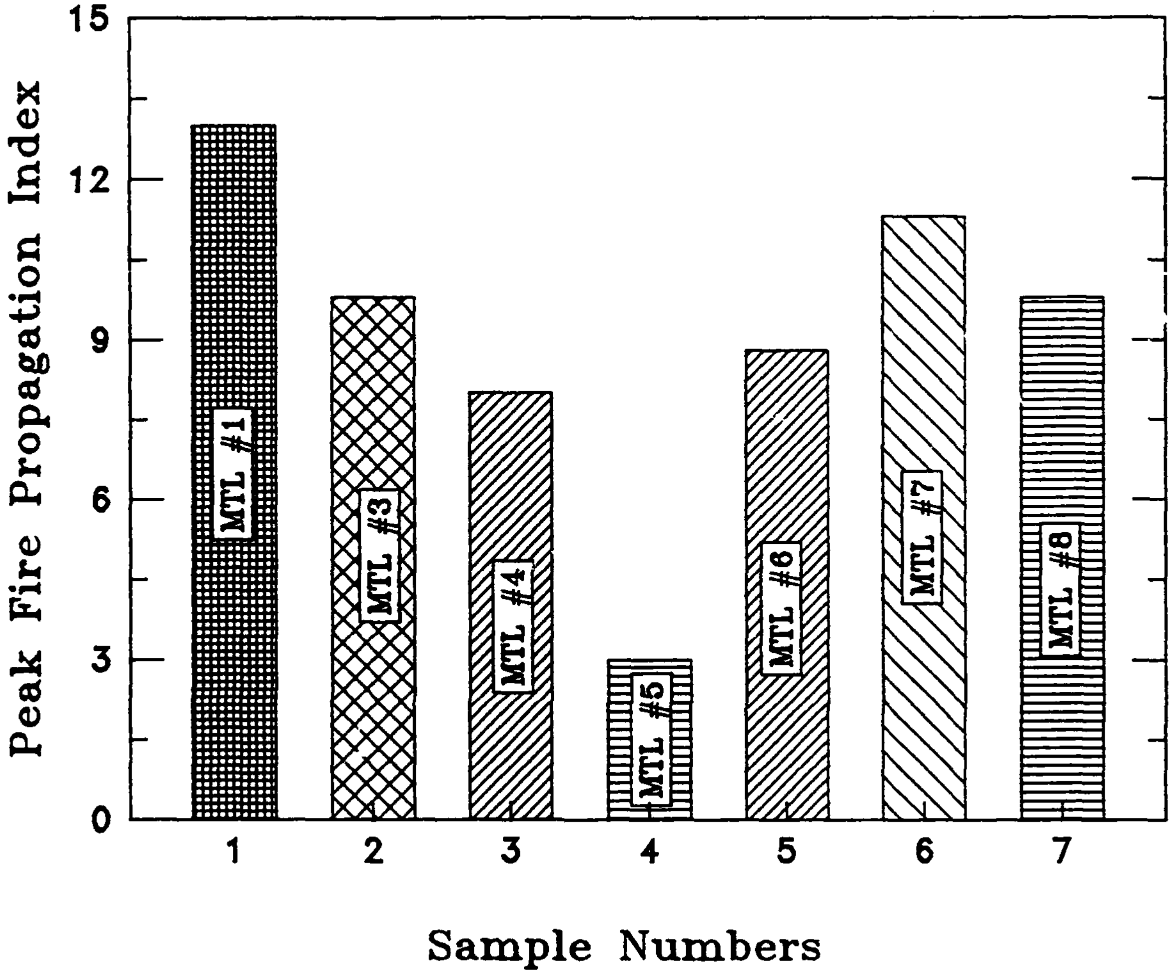

Figure 8. Fire Propagation Index for FRC Materials Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

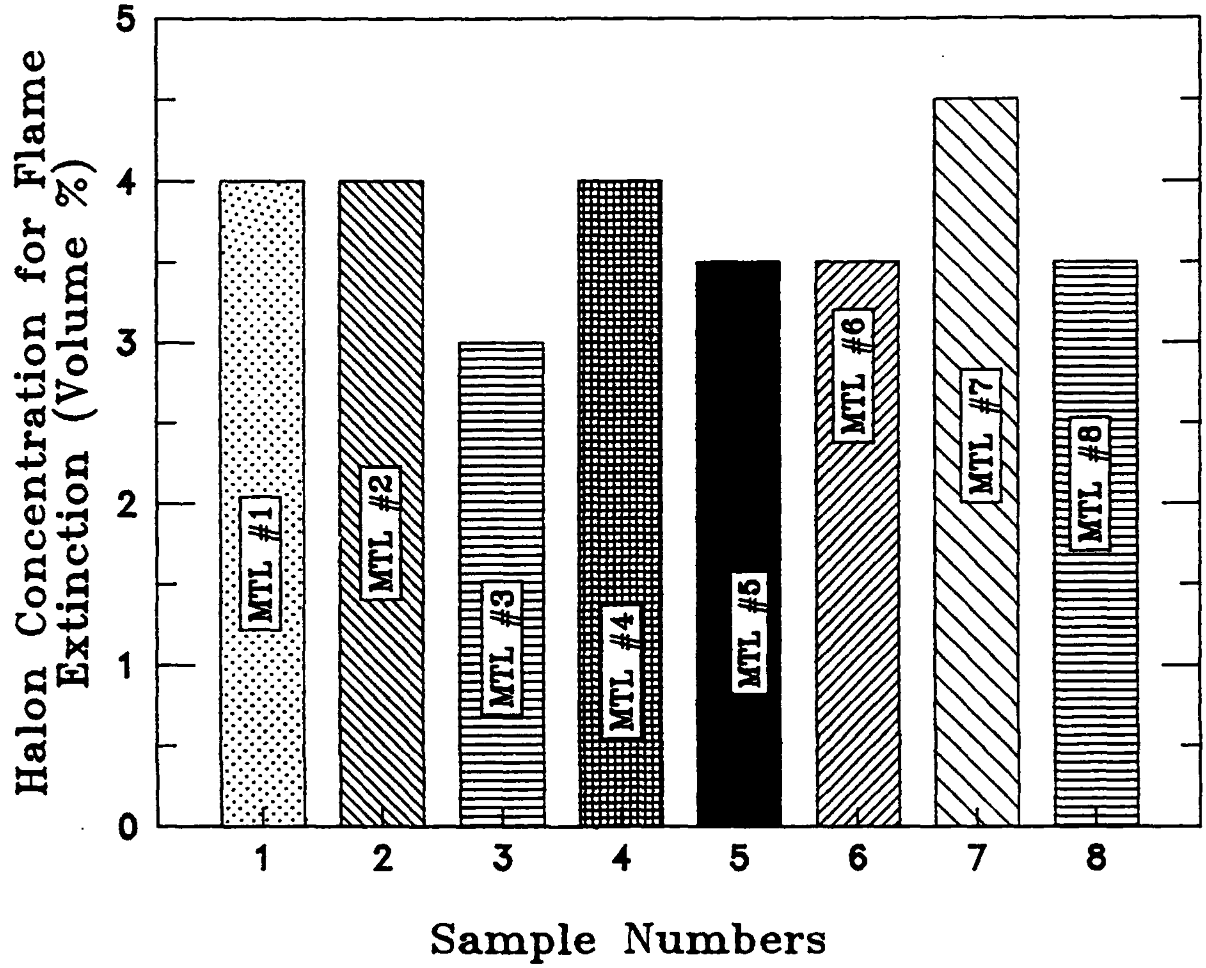

Figure 9. Halon 1301 Concentration in Volume Percent for Flame Extinction Fire for FRC Materials, Exposed to 60 kW/m^2 of External Heat Flux, Measured in the Factory Mutual Research Corporation's 50 kW-Scale Flammability Apparatus. Data for MTL # 1 to 5 Samples are Taken from Reference 1.

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The three FRC materials have higher resistance to ignition and flame propagation compared to ordinary combustibles. In comparison to the FRC materials (MTL #1 to #5) investigated in the previous study for the Army Materials Technology Lab, the three FRC materials were found to ignite more easily, and flame propagated beyond the ignition zone. Also, these three materials generated significantly higher amounts of material vapors, CO, smoke and heat than the materials examined earlier (MTL #1 to #5).

The Halon 1301 flame extinction data for the samples were found to be consistent with the design of the current suppression system for the crew compartment of Army combat vehicles.

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